The Ratio of Blue to Red Supergiants in Sextans A from HST Imaging [1]

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ABSTRACT

We have examined the ratio of blue to red (B/R) supergiants in the dwarf irregular galaxy Sextans A. The supergiants were identified in previously published stellar photometry measured from Hubble Space Telescope imaging. The high resolution imaging and low dust environment provided high photometric accuracy such that the main sequence and blue He-burning supergiants are clearly separated. This allows us to isolate the He-burning phase at both the red and blue ends of the so called "blue-loops". The B/R supergiant ratio provides an observational constraint on the relative lifetimes of these two phases which is a sensitive test for convection, mass loss, and rotation parameters. These parameters have direct implications for the period-luminosity relationship for Cepheid variable stars. Previous studies have used a single number to represent this ratio. However, since the B/R ratio is a fairly strong function of mass for a single age stellar population, both changes in recent star formation rate and choice of luminosity cut-off can dramatically affect the result. We have analyzed the ratio as a function of age, or equivalently, mass. This method eliminates the confusion of unknown star formation histories so that B/R can be a more reliable diagnostic tool. We compare the result with a model based on stellar evolution tracks of an appropriate metallicity. The functional form of the observed ratio matches the model extremely well. However, the observed B/R ratio is lower than the model by a factor of two. This result suggests that stellar rotation is an important effect in the evolution of these stars.

Subject headings: galaxies:individual (Sextans A) — galaxies:irregular — galaxies:Local Group — galaxies:stellar content — stars:evolution

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1. Introduction

The ratio of blue supergiants to red supergiants (B/R) is an important diagnostic for stellar evolution models. In particular, this ratio is a sensitive test for convection, mass loss, and rotation parameters (see Langer & Maeder (1995) and Maeder & Meynet (2001) for summaries; see also Salasnich, Bressan, & Chiosi (1999)). As Langer & Maeder (1995) discuss, some models reproduce the observed ratios for low metallicity, and others do so for high metallicity. However, there is not yet a self-consistent model that can reproduce (B/R) at both high and low metallicity. The effects of mass loss and rotation will also affect the period of variable stars (Maeder & Meynet 2001). Thus, any application of, for example, the Cepheid period-luminosity relationship must account for these parameters, and their relationship to metallicity.

Observational studies have been aimed at measuring absolute values of the B/R ratio and also measuring this ratio as a function of metallicity. Previous studies have measured the B/R ratio based on all stars brighter than a chosen absolute magnitude limit (see references in Langer & Maeder (1995)). Typically the calculation was restricted to very massive stars, ($> 15 M_{\odot}$). This provided a single ratio for each stellar population. For many of these studies this was the only reasonable method because of the limited photometric accuracy. However, there are several theoretical difficulties with this approach.

First, it has been known for some time that the B/R ratio is a fairly strong function of luminosity, and thus mass (e.g., Stothers (1969); Langer & Maeder (1995)). This makes comparison between galaxies difficult. For the comparison to be valid, the mass distribution of the supergiants would have to be identical above the magnitude limit. In other words, the star formation histories (SFHs) would have to be identical.

Second, it is obvious that the magnitude limits would need to be identical, but due to different distances of objects, this is not always practical. Additionally, when comparing galaxy populations to cluster populations, clusters almost never have a statistically significant population of very massive stars, so that the B/R ratios reported for clusters almost always use fainter limiting magnitudes.

Third, in ground-based observations of extragalactic objects, the blue supergiants are usually photometrically confused with the main sequence (MS). Thus, the number of blue supergiants includes those MS stars brighter than the chosen limit. Clearly these MS stars do not have red supergiant counterparts, producing a bias to higher B/R ratios which are not directly comparable to ratios derived from stellar evolution models. If the contamination by MS stars is accounted for in the models, again, the SFH has a strong effect on the resulting B/R ratio.

Clusters are not immune to these difficulties, even though they are isochronic. Since clusters have different ages, each cluster will have supergiant stars with masses corresponding to its particular age. Hence, valid comparison can only be made between clusters with the same age.

To properly use observations to constrain models, one must either incorporate the SFH into the model or eliminate this dependence from the observations. The most reliable way to eliminate the SFH from observations is to compare blue and red stars of the same age. In galaxies with mixed age populations the stars can be divided into age groups. Thus, one can calculate a function, or histogram, of the B/R ratio as a function of age, rather than a single number for the galaxy. In the following section we briefly describe the data and our method for calculating the B/R ratio. We compare the result with a model calculation. The final section discusses the results and the implications for stellar evolution models. Here we will use Hubble Space Telescope observations of Sextans A to demonstrate this method.

2. The B/R Supergiant Ratio in Sextans A

HST observations of the dwarf irregular galaxy Sextans A provided, for the first time, a clear photometric separation of MS stars from post-MS supergiants in their core He-burning (HeB) phase of evolution (Dohm-Palmer et al. 1997a). Using the isolated blue HeB stars, a detailed SFH was determined over the past 600 Myr (Dohm-Palmer et al. 1997b). These data were later enhanced by additional HST observations (Dohm-Palmer et al. 2001). Combining the two data sets provides nearly complete coverage of the optically visible portion of the galaxy. It also provides enough supergiants to perform a statistically feasible analysis of the B/R supergiant ratio. The combined data are shown for the upper part of the color magnitude diagram in Fig. 1.

From these data sets we have isolated the blue and red supergiants in the color-magnitude diagrams (CMDs). For the magnitude range of interest, the MS and BHeB populations show little or no change in color-index. Furthermore, these two populations are well separated compared to the photometric errors. To demonstrate this, we have calculated a histogram in color-index (Fig. 2) for the MS and BHeB stars with $-5.6 < M_V < -3.2$. The histogram shows an indisputable separation of these two populations. To determine the color-index selection limit for the BHeB stars, we simultaneously fit two Gaussian curves to the histogram. The result is shown in Fig. 2. The equality point between the two fit curves is $(V\text{-}I)_0 = -0.13$. We selected the BHeB stars as those stars redward of this limit.

From the simultaneous fit in Fig. 2 we can also estimate the degree of contamination of MS stars into the selected BHeB population. We integrated the curves of those fits and found that 5% of the BHeB stars are blueward of the selection limit. We also found that 6% of the of the BHeB counts are actually due to MS stars. Thus the net loss of stars from the blue count is approximately 1%. This is much smaller than the Poisson errors.

The red stars were selected interactively. Brighter than the RGB, the red supergiants are well isolated from other populations, so the exact selection region in the CMD is not important. The faint end of the red supergiants blends with both the AGB and the RGB. This sets a practical age limit for this calculation of ~ 200 Myr. Even though the observations in Dohm-Palmer et al. (2001) are much deeper than those in Dohm-Palmer et al. (1997b), the errors in the photometry and the completeness corrections for the supergiants of interest here are negligible.

We calculate the B/R ratio in age bins, rather than as a single number for the galaxy. By comparing blue and red stars of the same age we eliminate any dependence on the star formation rate (SFR). The SFR can in general, and does in Sextans A (Dohm-Palmer et al. 2001), change over the time periods for which supergiants exist. It is also crucial to separate the blue supergiants from the MS. MS stars and blue supergiants of the same magnitude have very different masses and ages. Thus, if these populations are mixed, the calculated ratio is extremely sensitive to both the star forming history as well as the initial mass function (IMF).

By separating the stars into age bins, the risk of contamination of the BHeB counts by MS stars is somewhat enhanced. For example, if, at a given luminosity, the number of MS stars greatly exceeds the number of BHeB stars, then the ∼5% of MS stars that will contaminate the BHeB stars could have a disproportionate effect on the BHeB star count in that bin. We have investigated this by plotting histograms similar to Figure 2 for each age bin, and find that the number of MS stars and BHeB stars is roughly comparable in each age bin. In many bins there is a clear gap between the two populations. Thus the contamination of MS stars into the BHeB star counts should be comparable to the number of BHeB stars lost to MS star counts in each bin. Overall, the effect of confusion between the MS and BHeB star counts is conservatively estimated to be less than 10% in each bin. That is, this will be a negligible effect on the outcome.

Table 1 shows the B/R ratio if we were to adopt a faint magnitude limit and calculate a single number for the galaxy. The first column is the adopted magnitude limit, and the second is the resulting B/R ratio. We include several magnitude criteria to demonstrate the dependence of this ratio on the adopted limit. The ratio generally decreases with fainter limits. We see here nearly a factor of two difference between the B/R ratio obtained for the most luminous stars (comparable to galaxy samples) and that obtained for stars with $M_V \leq -3$ (comparable to cluster samples).

To assign ages to the selected stars we have used the stellar evolution models of Schaller et al. (1992), combined with the stellar atmosphere models of LeJeune & Schaerer (2001). We will refer to these as the Geneva models. We used the Z=0.001 models to match the nebular abundance of Sextans A (Skillman, Kennicutt, & Hodge 1989). The models of this metallicity have been shown to be a good match to the stellar population (Dohm-Palmer et al. 2001), with the blue and red He-burning sequences in the correct predicted locations (see Fig. 1). For both the blue and red supergiants, each star can be assigned a nearly unambiguous age based on its position in the CMD. This is possible for two reasons. First, the lifetimes in these phases are very short compared to the age in which they are entered. Second, the luminosity of these phases is nearly a monotonic function of mass, and hence age.

To be complete, we have also applied a correction for the IMF. We used a power law function with a Salpeter slope of -1.35 (Salpeter 1955). For a given age, the mass of a blue supergiant will be slightly different from the mass of a red supergiant. However, the mass difference is so small that the resulting correction is negligible. We experimented with a wide range of IMF slopes, but found the B/R ratio to be insensitive to this parameter.

The result of the B/R ratio calculation is show in Fig. 3. The calculated values are given in Table 2. Note that the ages listed are the lower bounds of the histogram bins. The observed ratio is indicated with a histogram. The ratio starts near 2.5 and decreases with age. We have limited the calculation to ages older than 20 Myr. The evolution of younger, more massive, stars is highly uncertain (see Dohm-Palmer et al. (1997b) for a discussion).

To determine the predicted ratio we have created a simulated CMD using the Z=0.001 Geneva stellar evolution models. The simulated CMD was created using Monte Carlo techniques outlined by several authors (e.g., Tosi et al. (1991); Tolstoy & Saha (1996)). We did not incorporate photometric errors into this model. This would only serve to smooth the B/R ratio function in age, and we preferred a pristine model prediction. We also did not apply an incompleteness correction. The observed data is complete for the relevant populations.

There were 200,000 stars in the model, distributed with a power law IMF with a Salpeter slope (-1.35; Salpeter (1955)). The model used a constant star formation rate over the past 200 Myr. This resulted in 5502 blue supergiants and 3843 red supergiants. These stars were then divided into age bins in exactly the same manner as the observed data, including the IMF correction. The model prediction is included in Fig. 3 as a solid thick line.

The predicted ratio is approximately a factor of 2 larger than the observed ratio for all ages. However, the functional forms of the model and observations are remarkably similar. To emphasize this, we have plotted the model prediction reduced by a factor of two as a dashed line.

3. Errors in the Stellar Evolution Models

In the previous section we claimed to have eliminated the uncertainty of the star formation history from the calculation of the B/R ratio. Strictly speaking, this is only true if the adopted luminosity-age relationship is accurate for both the red and blue stars. We wish to emphasize three points concerning this issue.

While the stellar evolution models available today are not expected to be perfect, we have found that, in many respects, they are quite good in reproducing the observations. For example, (Dohm-Palmer et al. 1997b) showed that the stellar evolution models (from both the Geneva and Padua groups) of the appropriate metallicity reproduced the positions of the blue and red supergiants in the V, V-I color magnitude diagrams over their entire extent (also shown here in Figure 1). Given the uncertainties in these models (and the lack of very low metallicity, young stellar clusters with which to calibrate the models), we find this agreement both surprising and reassuring.

Second, we have found that the model predictions for the relative ages of the BHeB and MS stars agree remarkably well with the photometric observations in Sextans A (Dohm-Palmer et al.

2001). That is, we have compared the star formation histories calculated from MS stars and BHeB stars, and these two calculations show excellent agreement both qualitatively and quantitatively. The excellent agreement in the functional form of the star formation histories, which is only dependent on the adopted age-luminosity, and mass-luminosity relationships, gives us great confidence that, at least for the blue stars, these relationships are reliable.

Third, and perhaps more important, is that the present calculations are designed to constrain stellar evolution models. Again, we recognize that evolution models are not perfect, and that there is still much work to be done. However, that should not prevent us from using the available models to calculate quantities such as the star formation history. Such calculations, even given the possible inaccuracies due to less than perfect stellar evolution models, can still teach us much about the objects we study. We must simply accept the uncertainty as being the best one can do at present, just as we must accept the uncertainty in other calculations, such as distance estimates.

In the specific case of this paper, we have used stellar evolution models to self-consistently calculate the B/R ratio as a function of age. We find that the observed ratio does not match the predicted ratio. This implies that the model needs to be adjusted in some manner. It is possible that either, or both, the luminosity-age relationship and the relative lifetimes of the two phases need adjustment.

4. Discussion

The stars of Sextans A show that, in the specific case of the Geneva models, the predicted B/R ratio is a factor of 2 too large for this metallicity. However, these models do not incorporate stellar rotation. It has been shown by Maeder & Meynet (2001) that rotation increases the core mass during the He-burning phase. This inflates the atmosphere, increases mass loss, and pushes stars redward. Similar results have been found by Salasnich, Bressan, & Chiosi (1999) by increasing mass loss in the red supergiant phase. Thus, a smaller B/R ratio is predicted by incorporating rotation (Maeder & Meynet 2001). This is exactly the effect needed to account for our observations. It should be noted that the stars discussed by Maeder & Meynet (2001) have masses larger than the masses we consider here, however, the same general trends should apply.

Previous measurements of the B/R ratio have produced a single number for each population studied. As discussed in the introduction, such measurements can be deceiving, and comparisons with models must be made with care. For field stars, the star forming history influences this ratio making comparisons with other objects, and models, difficult. Even for isochronic populations, such as clusters, care must be taken to compare the result with a model of the appropriate age.

Langer & Maeder (1995) discuss the dependence of the B/R ratio on metallicity. The observational data they discuss suggest that this ratio increases with increasing metal abundance. This trend may in fact be true, however, the observational data points have not been adequately decoupled from age and star formation history. We have not resolved the problem of models not matching the B/R ratio at all metallicities. However, we have presented a method for removing ambiguities from the observed B/R ratio, making comparisons with models more meaningful. New calculations of stellar evolution including rotation at a metallicity appropriate to Sextans A would certainly be of interest.

We have demonstrated a technique for deriving a reliable constraint to evolution models of massive stars. This technique relies on clearly separating the blue supergiants from the MS. Unfortunately this may limit the number of objects available for analysis. High resolution imaging, such as with the HST, is required for objects with distance of order 1 Mpc or further. Additionally, in higher metallicity environments, dust can significantly broaden these features in the color magnitude diagram. In which case, multi-color photometry will be required to correct for line-of-sight reddening effects.

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Fig. 1.— The color-magnitude diagram for Sextans A. The stellar evolution tracks for the adopted Z=0.001 Geneva models (see text) are also plotted. These are labeled with the starting mass in Solar units. Notice that the ends of the blue loops in the models align with the observed blue and red supergiant sequences. We have indicated the age bins for the blue and red supergiant sequences on the left and right respectively. Notice that the age-luminosity relationship for the blue and red stars is different. Thus, limits based on magnitude alone would result in mixing different age populations.

Table 1. B/R Ratio Based on a Magnitude Limit

M_V	B/R ratio
−6.0	3.25
−5.5	2.70
−5.0	2.78
−4.5	2.61
−4.0	1.77
−3.5	1.76
−3.0	1.85

Table 2. The B/R ratio as a Function of Age

Age (Myr)	B/R ratio
20	2.55
35	1.54
50	0.70
65	1.28
80	0.90
95	0.73
110	0.66
125	0.43

Fig. 2.— A color-index histogram of Sextans A stars with absolute V magnitude between -5.6 and -3.2. This is the magnitude range used in the B/R ratio calculation. The MS and BHeB populations are clearly well separated. We have simultaneously fit two Gaussian curves to the histogram. The separate fits are shown as dashed lines, and the sum of the two is shown as a solid line. We have also indicated the equality point with a vertical line at $(V\text{-}I)_0 = -0.13$.

Fig. 3.— The B/R ratio for the dI galaxy Sextans A. The histogram is the observed ratio as a function of age. Stars were divided into age bins using the stellar evolution models of Schaller et al. (1992). The error bars reflect Poisson errors. The thick line is the ratio determined from a Monte Carlo CMD model using the stellar evolution models of Schaller et al. (1992), with atmospheric models applied by LeJeune & Schaerer (2001). The error bars also reflect Poisson errors. The dashed line is the model reduced by a factor of 2. Notice how well the functional form of the observations matches that of the model. However, the model values are twice as large as the observations.